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Engineering Design File

Landfill Compaction/Subsidence Study

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This calculation predicts the amount of subsidence in the cover of the INEEL CERCLA Disposal Facility landfill. Settlement is caused by consolidation of the subsurface soils underlying the landfill, waste material settlement, and settlement in the cover itself. This calculation estimates subsidence in the cover and determines allowable settlement. It also provides recommendations for compacting waste materials to reduce settlement.

6. Review (R) and Approval (A) and Acceptance (Ac) Signatures:
(See instructions for definitions of terms and significance of signatures.)

	R/A	Typed Name/Organization	Signature	Date
Performer		Phillip Crouse/ Montgomery Watson	Phillip S. Crouse	05/14/02
Checker	R	(Same as Independent Peer Reviewer)		05/14/02
Independent Peer Reviewer	A	Marty Doornbos/ BBWI	Marty Doornbos	05/14/02
Approver	A	Thomas Borschel/ BBWI	Thomas F. Borschel	05/14/02
Requestor	Ac	Don Vernon/ BBWI	D. Vernon	05/14/02

7. Distribution: (Name and Mail Stop)
M. Doornbos, MS 3930; D. Vernon, MS 3930; T. Borschel, MS 3930

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ABSTRACT

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ACRONYMS

ASTM	American Society for Testing and Material
CERCLA	Comprehensive Environmental, Response, and Compensation Act
CFR	Code of Federal Regulations
DOE-ID	Department of Energy Idaho Operations Office
EDF	engineering design file
EPA	Environmental Protection Agency
FS	factor of safety
ICDF	INEEL CERCLA Disposal Facility
INEEL	Idaho National Engineering and Environmental Laboratory
O&M	operations and maintenance
PPE	personal protective equipment
SBL	soil bentonite liner
WAC	Waste Acceptance Criteria

Landfill Compaction/Subsidence Study

1. PURPOSE

The purpose of this calculation is two-fold: first, to determine the allowable INEEL CERCLA Disposal Facility (ICDF) landfill cover settlement; second, to develop a suggested method for compaction and testing to minimize consolidation in the waste materials placed in the ICDF landfill. The top slope of the ICDF cover is a function of subsidence, erosion, surface water runoff, geometry, and infiltration. This calculation addresses subsidence. The "Hydrologic Cover Model" (EDF-ER-279) design study addresses the cap design from an infiltration perspective. The "Liner and Final Cover Long Term Performance Evaluation" (EDF-ER-281) design study combines the results from the subsidence and infiltration calculations, along with the other cover design consideration to determine the overall final cover grades and cover design.

The second part of this calculation provides a toolbox for waste compaction methods and procedures that can be used to minimize settlement in the waste. The final waste compaction requirements will be determined during waste placement.

2. METHOD

2.1 Cover Subsidence

The ICDF landfill will contain Comprehensive Environmental, Response, and Compensation Act (CERCLA)-generated contaminated bulk soil, debris (i.e., rubble, concrete, wood, drums, boxes, personal protective equipment [PPE], and metals), and treated waste that are generated at the Idaho National Engineering and Environmental Laboratory (INEEL) and meet the agency-approved Waste Acceptance Criteria (WAC) for the ICDF landfill. Total subsidence in the cover will be a cumulative of settlement amounts due to deformation in the landfill components listed below:

- Consolidation of the waste that is soil
- Consolidation of the waste due to degradation of waste debris
- Consolidation due to voids left in containerized waste
- Consolidation of the soil bentonite liner (SBL) and foundation soils
- Consolidation of the cover itself.

The majority of the waste in the landfill will be soil comprised of the sands and gravels found in the near surface soils around the INEEL site (DOE-ID 2000). The waste soils will be compacted to minimize settlement. Additionally, settlement in the waste will be immediate as the waste is placed in the landfill and during construction of the cover.

The volume of debris is expected to be small. Debris can be categorized as non-degradational and degradational. Non-degradational debris includes materials such as asphalt and concrete. Material such as wood, plastic, and metal can degrade due to biochemical, oxidation, and corrosion-type reactions creating voids in the waste that may result in long-term settlement. Containerized waste (e.g., drums) may contain up to 5% void space that can collapse due to loads from the overlying waste as shown in "Waste-Soil Design Ratio Calculations" (EDF-ER-277). Debris will be preprocessed if necessary to minimize mechanical compression resulting from distortion, bending, or reorientation. The maximum long-term differential settlement in the liner and foundation soils is estimated to be 1.2 ft as shown in "Subsurface Consolidation" (EDF-ER-266). The final cover grades will be adequately sloped to accommodate, at a minimum, this amount of settlement. The cover is comprised mainly of earthen materials that will settle due to this weight. The cover layers comprised of fine-grain soil will consolidate the most over the long term. These include the soil bentonite liner (SBL) barrier layer and engineered structural fill water storage layer. This amount of settlement will be calculated using standard Terzaghi consolidation theory (Holtz and Kovacs 1981). Lastly, the cover final grades, after all subsidence has occurred, must maintain a positive slope to promote drainage and protect the integrity of the cover system.

In summary, the final cap slope required to account for subsidence will be a function of the following considerations:

- Subsurface consolidation: differential settlement amount of 1.2 ft (EDF-ER-266)
- Degradable debris consolidation: settlement varies depending on the thickness of debris
- Void space in containerized waste: settlement amount of 1 ft

- Cover consolidation: constant settlement amount calculated herein

- Minimum final cover slope of 3% after subsidence.

Nomagraphs are developed for various cover slopes and lengths based on the above considerations. The Nomagraphs were used to determine the predicted maximum allowable settlement based on the final cover slope. A design ratio was computed by dividing the allowable settlement by the predicted settlement, as shown below.

$$\text{Design Ratio} = \frac{(\text{Cover Settlement})_{\text{allowable}}}{(\text{Cover Settlement})_{\text{predicted}}} \qquad (1)$$

Where

$(\text{Cover Settlement})_{\text{allowable}}$ is the maximum settlement in the cover that can occur and still maintain the required minimum slope.

$(\text{Cover Settlement})_{\text{predicted}}$ is the predicted settlement based on subsurface consolidation, degradable debris consolidation, void space in containers, and settlement within the cover itself.

3. COVER SETTLEMENT

The integrity of the cover must be maintained for the long term (the design life of 1,000 years). This is achieved by overbuilding the cover to accommodate predicted settlement and minimize strain in the cover components.

The total predicted settlement in the ICDF landfill cover is summarized in Table 3-1.

Table 3-1. Summary of predicted cover settlement.

Landfill Component	Long-term Predicted Settlement (ft)
Foundation and Liner	1.2
Waste as Soil	0[a]
Waste as Degradable Debris	Varies (dependent on debris thickness)
Cover	0.1
Total Predicted Cover Settlement without Degradable Debris	**1.3**

a. Settlement will be immediate during operation and cover construction

The settlement calculation for the foundation and liner soils is described in "Subsurface Consolidation" (EDF-ER-266). The amount of settlement caused by degraded debris or debris subsidence is discussed in Section 3.1. The settlement in the cover itself is calculated in Appendix A of this document. The maximum volume of each type of containerized waste is provided in the "Waste-Soil Design Ratio Calculations" (EDF-ER-277). The maximum void ratio is 5% based on the ICDF Landfill WAC (DOE-ID 2001).

Landfill covers must maintain a positive slope to promote surface water runoff (Code of Federal Regulations [(CFR)] 264.310). The EPA recommends a final top slope between 3 and 5%, after settlement has occurred (EPA 1989). The allowable cap settlement for slope lengths between 300 and 500 ft is shown in Figure 3-1. The plot includes a minimum slope of 3% and a limiting strain value of 0.1%.

The proposed cover surface will have a slope of 7% (EDF-ER-281) and a length of 387 ft measured on its shortest side. Based on review of Figure 3-1, the cap could accommodate additional settlement (i.e., after subsurface consolidation, cover settlement, and the maximum strain are accounted for) of 13 ft. The calculation used to develop the graph in Figure 3-1 is provided in Appendix B.

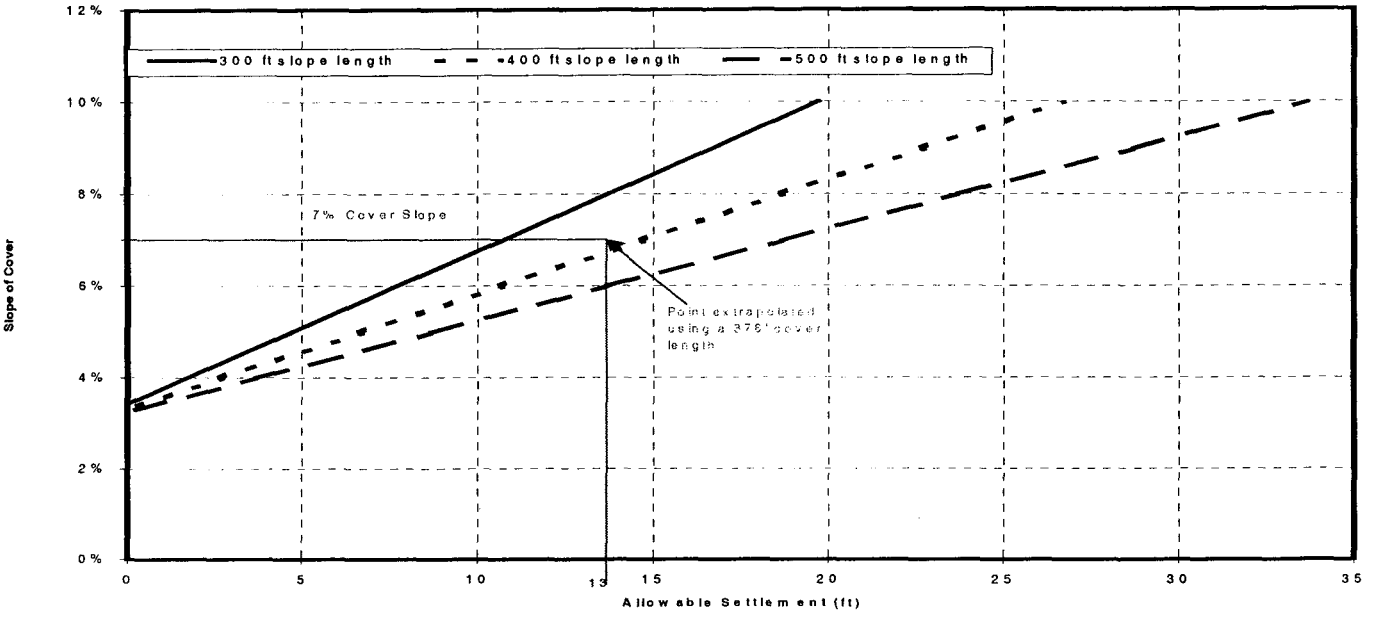

Figure 3-1. Allowable settlement vs. cover slope to maintain a 3% slope.

3.1 Settlement of Waste Debris

A portion of the waste placed in the landfill will be non-soil material. These materials will be debris such as rubble, concrete, wood, PPE, metals, containerized waste, and treated waste that are generated at the INEEL and meet the agency-approved WAC for the ICDF. Containerized waste will contain up to 5% void space and may crush under the overlying waste. The volume of waste consists predominantly of contaminated soils so the volume of debris is expected to be small (EDF-ER-264). Additionally, non-soil material will be preprocessed, if necessary, to minimize mechanical compression resulting from distortion, bending, or reorientation of the materials. However, non-soil debris such as wood, plastic, and metal can create potential settlement due to corrosion, oxidation, biochemical decomposition, and compression of containers.

In municipal and construction debris landfills, where degradable debris accounts for a majority of the air space, long-term secondary settlement can be on the order of 15% of the waste thickness).[a] This amount of settlement is conservative for the ICDF landfill since it will contain only contaminated soil and debris without municipal solid waste. Additionally, the actual volume of degradable debris is expected to be small in the ICDF landfill (EDF-ER-264). The amount of settlement caused by degrading debris will be a function of its thickness in the landfill. This simple relationship is shown in Figure 3-2.

The maximum amount of settlement due to degradable type debris potentially could be on the order of 5 ft for a debris thickness of 34 ft (the total thickness of waste in the landfill). Additionally, the cover could settle an additional 1 ft due to 55-gallon drums collapsing over time. The total predicted settlement

[a] Fasset, 1993, Unpublished paper entitled "Geotechnical Properties of Municipal Solid Waste and Their Use in Landfill Design."

of 6 ft is well within the allowable settlement of 13 ft based on the proposed cover grade at 7%. Based on the analysis, the cover design provides a design ratio of 2 for long-term settlement, as shown below.

$$\text{Design Ratio} = \frac{(\text{Cover Settlement})_{\text{allowable}}}{(\text{Cover Settlement})_{\text{predicted}}} \qquad (2)$$

$$= \frac{13 \text{ ft}}{6 \text{ ft}} = 2$$

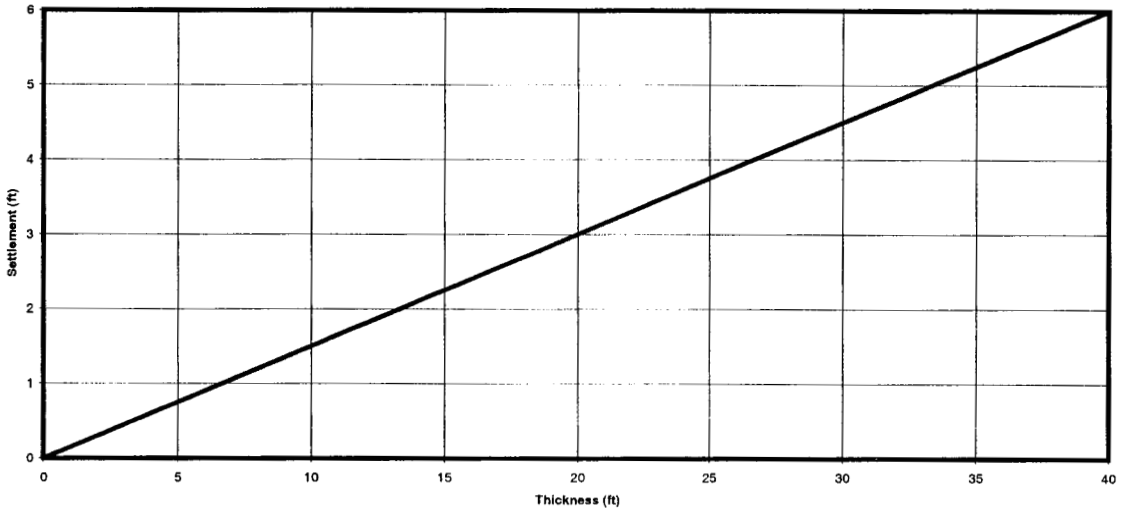

Figure 3-2. Debris thickness vs. settlement.

3.2 Final Cover Grade Nomagraph

Combining the plots in Figures 3-1 and 3-2 provides a range of allowable thickness of degradable debris and voids in containerized waste for given cap slopes and slope lengths (Figure 3-3). This nomograph was used as a guide for completing the final cover design for the ICDF landfill and WAC.

Based on review of Figure 3-3, a final cover grade constructed at a minimum slope of 4% would allow a maximum total debris thickness of approximately 12 ft with design ratio equal to 1. A cover constructed at a grade of 7% allows for a total debris thickness of 35 ft and a total predicted settlement of 6 ft with a design ratio of 2. A cover slope constructed at a maximum slope of 7% has been shown to be stable and resistant to wind and water erosion based on the calculations performed in the "Liner and Final Cover Long Term Performance Evaluation" (EDF-ER-281).

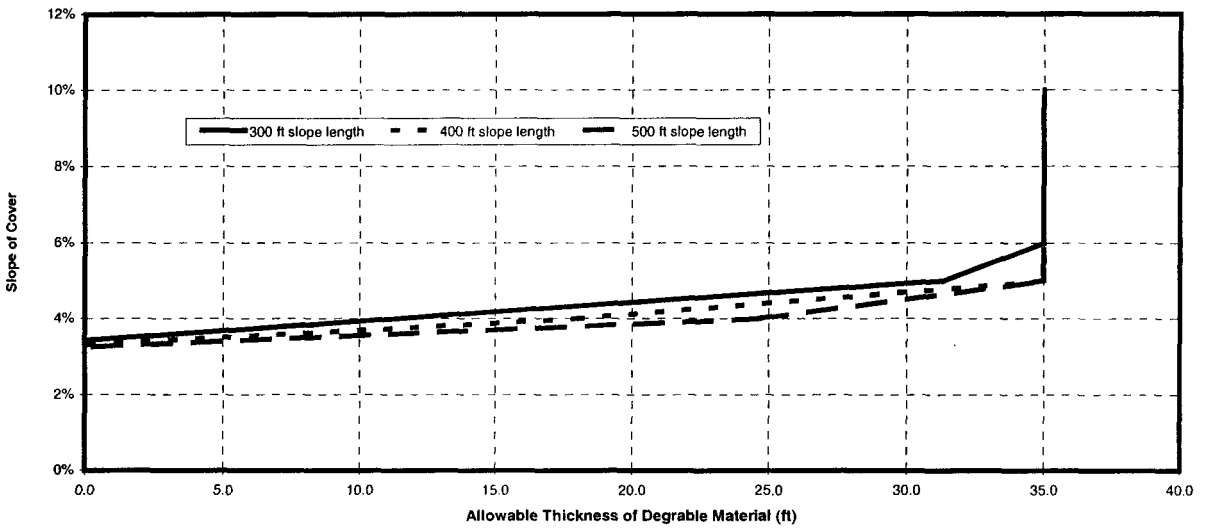

Figure 3-3. Allowable degradable material and other voids vs. cover slope to maintain a 3% slope.

This exercise demonstrates that the cover can accommodate settlement due to foundation consolidation, waste debris settlement, cover settlement, and voids in containerized waste having a minimum slope of 4%. Calculations performed in the "Liner and Final Cover Long Term Performance Evaluation" (EDF-ER-281) demonstrate that the cover can maintain its integrity over the long term having a slope of 7%. This slope can accommodate a predicted settlement with a design ratio of 2 and is recommended for the ICDF cover.

4. WASTE COMPACTION

4.1 Compaction Equipment and Methods

Settlement in waste from consolidation will be immediate and occur during the construction of the cover due to the granular nature of the waste soils. These types of soils typically are easier to compact as compared to fine-grained soils. Settlement due to voids around debris will be minimal since the debris can be broken down into small pieces and mixed with soil as evenly as possible throughout the landfill. The third and less controllable factor is settlement due to degradation of debris. The volume of this type of waste is expected to be small and can be accommodated in the final design of the ICDF landfill cover using the nomagraph prepared in this study.

Based on this understanding, a toolbox of equipment and methods is provided that can be used for waste placement in the ICDF Landfill. The specific compaction requirements will be based on production, economic, and exposure factors during the operation of the ICDF Complex. Suggested compaction methods, equipment, and testing methods are provided in Table 4-1. These recommendations will ensure uniform compaction of the waste and maximize use of available air space. Additional compaction of waste will be achieved from loading due to haul truck and heavy equipment traffic.

Table 4-1. Equipment and tests for determining compaction of waste.

Material Description	Recommended Compaction Method	Maximum Lift Thickness (in.)	Applicable Test Methods	Remarks
Fine- or Coarse-grained Soils	Medium weight vibratory roller (dynamic forces of 20 to 27 tons)	24	Nuclear Moisture-Density Gage (ASTM D2922)	• The gage contains radioactive source and may not be allowed on-site. • Correction for rock may be required. • Correction for background radiation required. • No sample collection required. • Requires personnel to be in contact with waste.
	Landfill Compactor	12		
			Sand Cone (ASTM D1556)	• Requires collection of sample and moisture content determination. • Requires handling of waste. • Requires personnel to be in contact with waste.

Table 4-1. (continued).

Material Description	Recommended Compaction Method	Maximum Lift Thickness (in.)	Applicable Test Methods	Remarks
			Rubber Balloon Methods (ASTM D2167)	• Requires collection of sample and moisture content determination. • Requires handling of waste. • Requires personnel to be in contact with waste.
			Visual Observation	• Observation of number of passes, lift thickness, and moisture conditions gives qualitative assessment of compaction. • Test pads can be used to determine acceptable compaction methods. • Personnel can observe at safe distance from waste.
Debris and Rock	Landfill compactor	48	Visual Observation	• Observation of number of passes, lift thickness, and moisture conditions gives qualitative assessment of compaction. • Personnel can observe at safe distance from waste.

Soil should be mixed with the debris during placement to fill voids. Waste should be placed by the compactor whenever possible. The compacting wheels of the compactor should perform at least three passes over all waste with one pass defined as the compactor travelling forward and backward over the area. Alternatively, if a sheepsfoot compactor is in use, compaction should be performed until the feet of the compactor are no longer penetrating the soil. Compaction should occur with the material in a moist condition such that dust and pumping of the material is not observed.

4.2 Compaction Requirements

The suggested compaction requirements for the waste materials are provided in Table 4-2.

Table 4-2. Suggested waste compaction requirements.

Waste	Requirement	Observation
Fine- or Coarse-grained Soils with fines	Minimum three passes with compaction equipment, or number of passes necessary to achieve 90 to 95% relative compaction.	No visible dust or pumping

Table 4-2. (continued).

Waste	Requirement	Observation
Coarse-grained Soils (free draining)	Minimum three passes with compaction equipment, or number of passes necessary to achieve 90 to 95% relative compaction.	No visible dust or pumping
< 5% fines		
Rock and Debris	Mixed with soils during placement.	No visible dust or pumping
	Three passes with a compactor.	Material meets sizing criteria

5. REFERENCES

40 CFR 264, 1999, "Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities," *Code of Federal Regulations,* Office of the Federal Register, July 1, 1999.

ASTM D1556-00, 1996, "Density and Unit Weight of Soil in Place by the Sand-Cone Method," American Society for Testing and Materials, 1996.

ASTM D2167-94, 1994, "Density and Unit Weight of Soil in Place by the Rubber Balloon Method," American Society for Testing and Materials, 1994.

ASTM D2922-96e1, 1996 (2001), "Standard Test Methods for Density of Soil-Aggregate in Place by Nuclear Methods," American Society for Testing and Materials, (reapproved 2001).

DOE-ID, 2002, *Waste Acceptance Criteria for ICDF Landfill*, DOE/ID-10865, Rev. 2, U.S. Department of Energy Idaho Operations Office, Idaho Falls, Idaho, May 2002.

DOE-ID, 2000, *Geotechnical Report for the Conceptual Design of the INEEL CERCLA Disposal Facility at Waste Area Group 3, Operable Unit 3-13,* DOE/ID-10812, Rev. 0, Department of Energy Idaho Office Operations, Idaho Falls, Idaho.

EDF-ER-264, 2001, "INEEL CERCLA Disposal Facility Design Inventory," Rev. A, Environmental Restoration Program, Idaho National Engineering and Environmental Laboratory, March 2001.

EDF-ER-266, 2002, "Subsurface Consolidation," Rev. 1, Environmental Restoration Program, Idaho National Engineering and Environmental Laboratory, May 2002.

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EDF-ER-279, 2002, "Hydrologic Modeling of Final Cover," Rev. 2, Environmental Restoration Program, Idaho National Engineering and Environmental Laboratory, May 2002.

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Holtz, R.D. and W.D. Kovacs, 1981, *An Introduction to Geotechnical Engineering,* Prentice-Hall, New York, N.Y.

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Appendix A

Settlement of Cover

Consolidation Settlement Calculation for Compacted Clay Cover Due to Load from Cover

Assume: Water table is not present (used 100 ft).
Compacted clay cover layer (2 ft thick) is placed moist and will consolidate.
Compacted clay liner (po'=1,000psf)

Soil Cover γ_{total} = 133.5 (pcf) γ_{total} = 133.5 (pcf)

$\Delta p'$ total = 15.5 feet of 133.5 pcf material = 2069.3 psf

depth of water = 100 (ft)
Unit Weight of Water = 62.4 (pcf)

Calculations: For settlement at center point of Landfill.

	Depth																
Layer	Top	Bottom	Mid-Layer	Thickness	Soil Unit Weight	$\Delta p'$ total	p_o	u	p_c'	p_i'	p_f'	C_r	C_c	Est. in situ Void Ratio	Re-consolidation Settlement	Consolidation Settlement	Combined ΔH
	(ft)	(ft)	(ft)	H (ft)	γ_{total} (pcf)	(psf)	(psf)	(psf)	(psf)	(psf)	(psf)			(e_o)	(ft)	(ft)	(ft)
1	0	2	1	2.00	120.4	2069	120	0	1000	-	2069	-	0.198	0.61	0.00	0.1	0.1
														Total Reconsolidation Settlement =	0.00		
														Total Consolidation Settlement =		0.1	
															Total Combined Settlement =		**0.1**

Notes:
1) C_c for clay liner is the highest of the empirical values.
2) Assume compactive effort creates p'o of 1,000 psf and rebound does not take place.

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Appendix B

Nomagraph Development

Appendix B

Nomagraph Development

Performed By: Craig Burger | Project Name: INEEL ICDF | Project #: 2470178
Checked By: Phillip Crouse | Date: 4/11/01

B.1 LANDFILL COMPACTION SUBSIDENCE CALCULATION

B.1.1 PURPOSE

The purpose of this calculation is to determine the minimum required cover slope to ensure positive drainage off of the slope following subsidence of the landfill. In addition, the cover slope required to meet strain deformation criteria for the landfill cover is considered.

B. 1.2 METHOD

Settlement over time for the landfill cap will consist of consolidation settlement in fine-grained soils under the cap and settlement due to degradation of materials and subsequent volume reduction in the waste materials.

$S_t = S_c + S_{deg}$

Where,

S_c = Consolidation settlement

S_{deg} = Settlement due to degradable debris.

Terzaghi's Consolidation Theory is used to determine the subsurface soils, the landfill liner system, and the cover placed over the waste. The majority of the waste is assumed to be coarse-grained soils that will settle immediately upon placement of a load. The consolidation calculation for the subsurface soils and liner system is shown in EDF-ER-266.

Degradable material is assumed to settle by approximately 15% as suggested by Fasset, 1993.

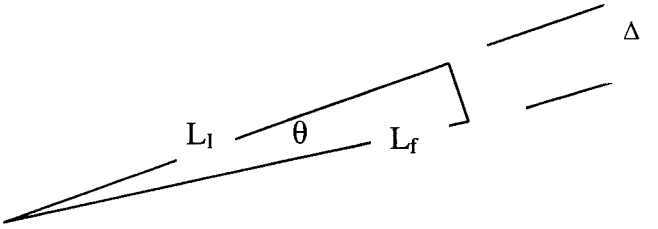
This study focuses on the settlement impacts to the ICDF landfill cover due to the consolidation of the underlying soils and potential settlement due to degradable debris. The calculation is performed to determine how much degradable material can be placed in the landfill while maintaining the minimum 3% cover slope for three different slope lengths, 300, 400, and 500 feet, and for initial cover slopes up to 10%.

The permissible tensile strain is determined by iteratively calculating the settlement that corresponds to a strain of 0.1% in the cover materials.

B.2 DIFFERENTIAL SETTLEMENT AND ALLOWABLE LINER STRAIN

The strain is calculated as follows:

$$\varepsilon = \frac{L_f - L_l}{L_l}$$



Where,

ε = Strain

L_f = Final length

L_l = The length on which the distortion acts

S_d = Total settlement

θ = Angle of rotation

Δ = S_d

The calculation was performed in the attached spreadsheet and an example is included below:

$$L_l = 300\,ft$$

$$\sin\theta = \left(\frac{14\,ft}{300\,ft}\right) = 0.047\,radians$$

$$L_f = \frac{300\,ft}{\cos(0.047)} = 300.33$$

$$\varepsilon = \frac{300.33\,ft - 300\,ft}{300\,ft} = \frac{0.33\,ft}{300\,ft} \times 100 = 0.1\%$$

B.2.1 ASSUMPTIONS

- 1.2 ft of consolidation settlement will occur in the subsurface soils and liner (EDF-ER-266)
- 0.1 ft of consolidation settlement will occur in the cover
- Degradable waste will settle 15% of its thickness

- The permissible strain is governed by the clay cover which maintains integrity up to 0.1 to 1% tensile strain

B.2.2 CALCULATIONS

Calculations are performed on the attached spreadsheets and detailed in the EDF.

B.2.3 RESULTS/CONCLUSIONS

The results are presented in nomographs that can be used to determine the allowable thickness of biodegradable material that may be placed for a given cover length and slope. Results and conclusions are described in detail in the EDF.

B.2.4 REFERENCES

Fasset, 1993, Unpublished paper entitled "Geotechnical Properties of Municipal Solid Waste and Their Use in Landfill Design."

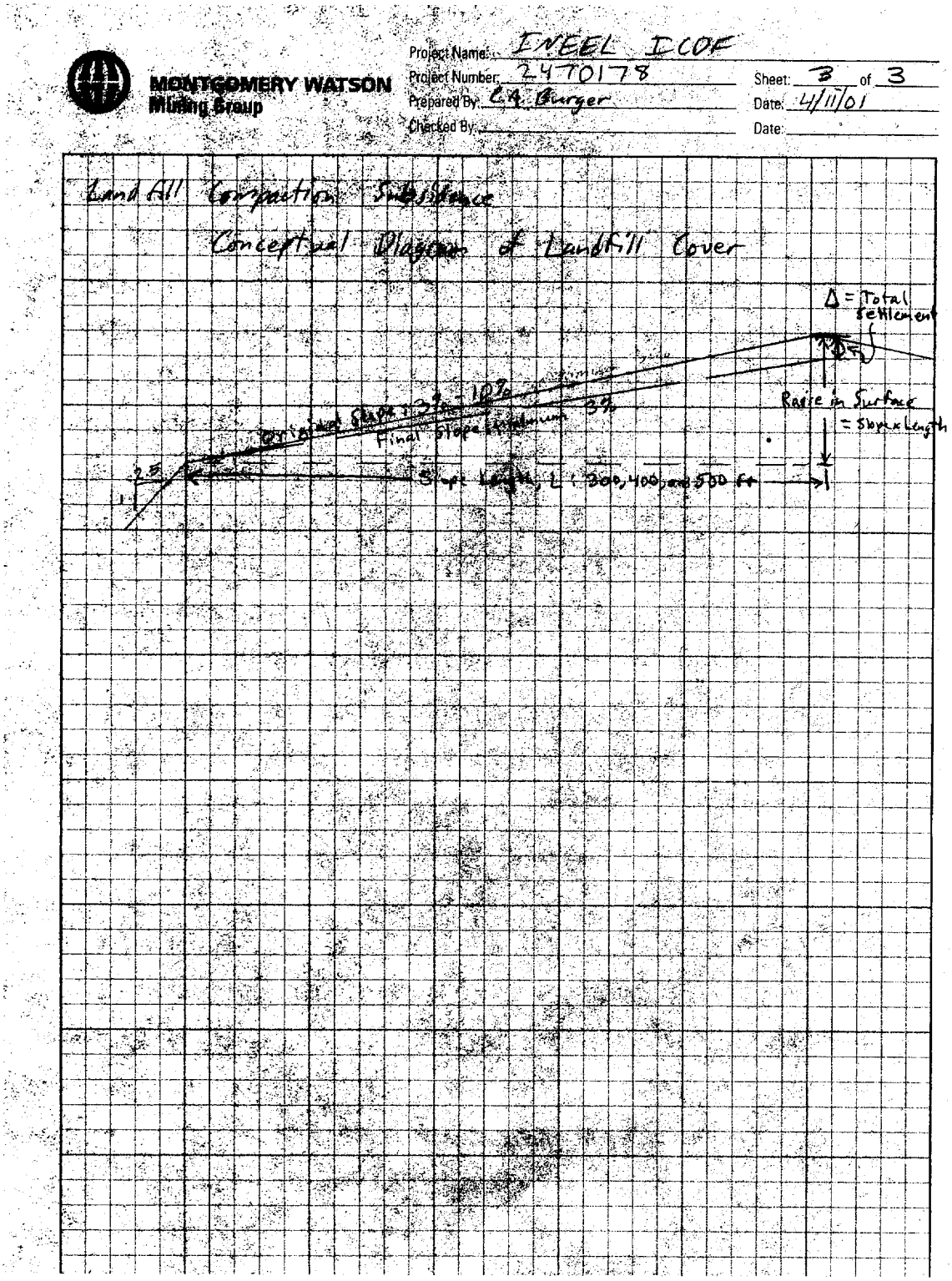


Figure B-1. Landfill compaction subsidence/conceptual diagram of landfill cover.

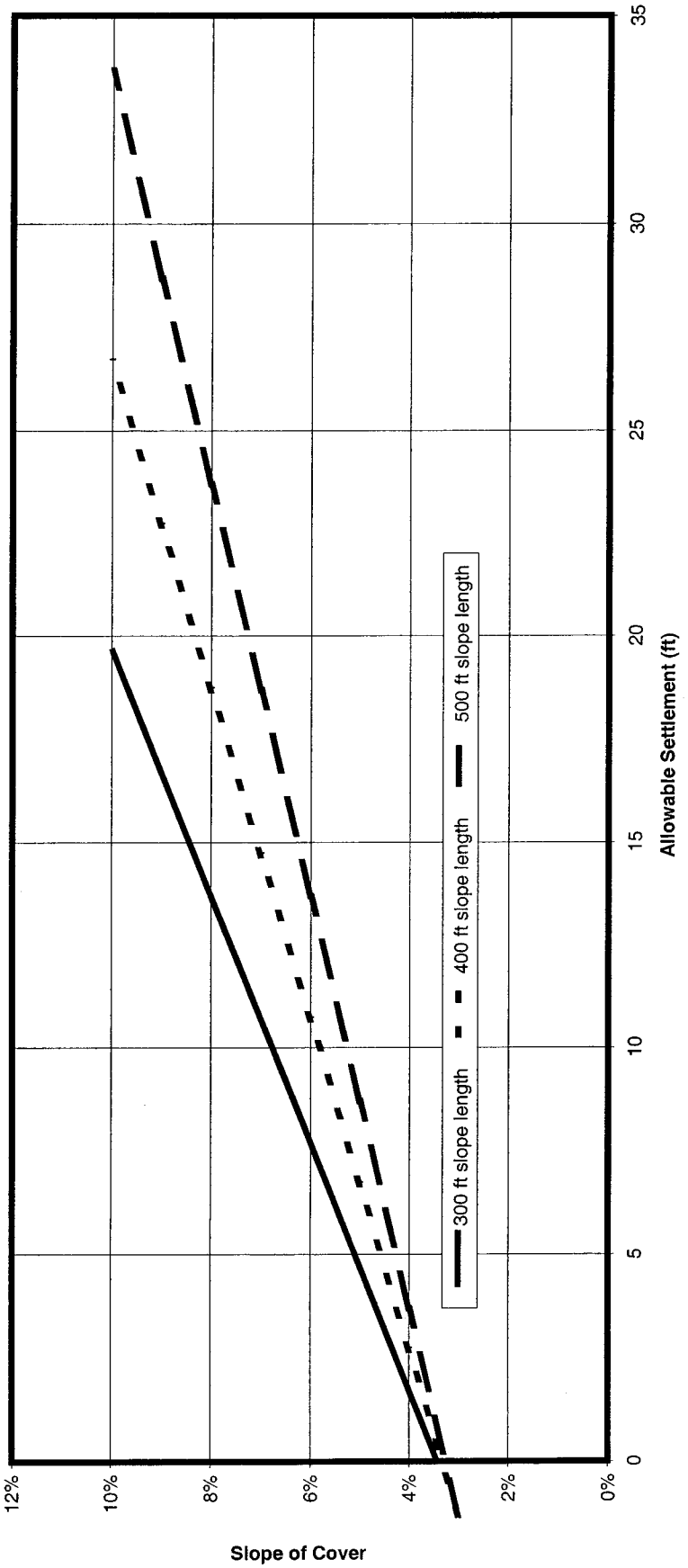


Figure B-2. Allowable settlement vs. cover slope to maintain a 3% slope (Figure 3-1 in text).

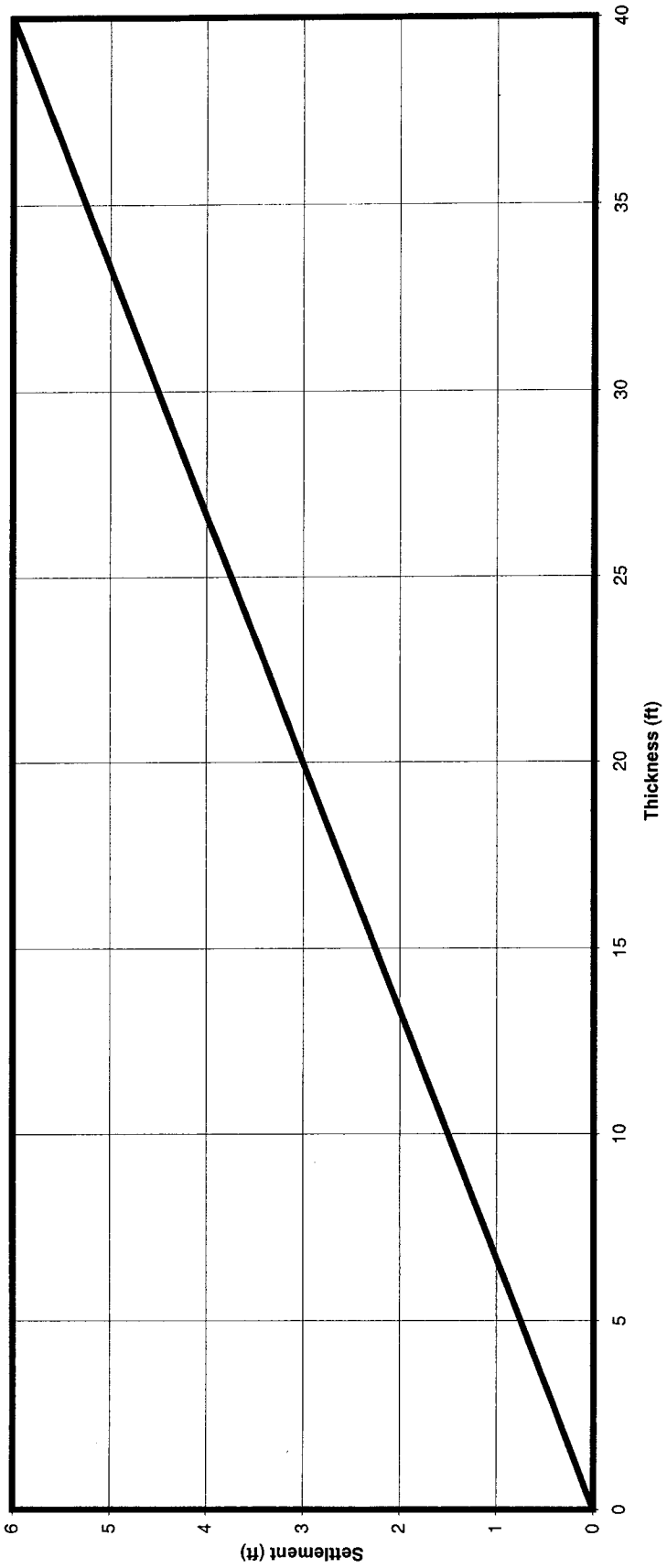


Figure B-3. Degradable material thickness vs. settlement (Figure 4-1 in text).

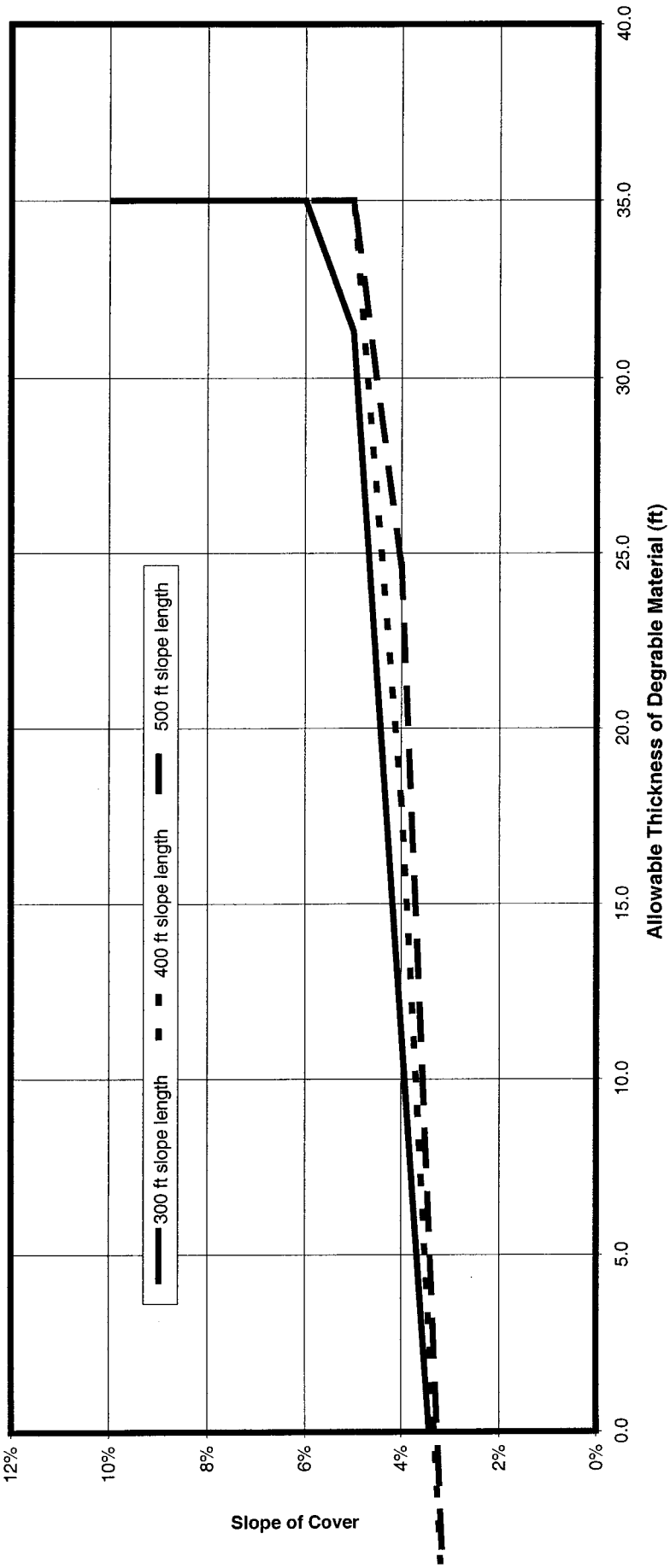


Figure B-4. Allowable degradable material thickness vs. cover slope to maintain a 3% slope (Figure 4-2 in text).

Cover Slope Settlement Calculation
Calculation performed for the center of the landfill

Cap slope	Raise in surface at landfill center (ft)	Subsurface Consolidation Settlement (ft)	Cover Consolidation Settlement (ft)	Raise in surface to maintain 3% slope (ft)	Maximum settlement to maintain 3% slope (ft)	Allowable degradable thickness (ft)	Length of slope (ft) : 400
0.03	12	1.2	0.1	12	-1.3	-8.7	15%
0.04	16	1.2	0.1	12	2.7	18.0	percent degradable settlement
0.05	20	1.2	0.1	12	6.7	35.0	
0.06	24	1.2	0.1	12	10.7	35.0	
0.07	28	1.2	0.1	12	14.7	35.0	
0.08	32	1.2	0.1	12	18.7	35.0	
0.09	36	1.2	0.1	12	22.7	35.0	
0.1	40	1.2	0.1	12	26.7	35.0	

	Maximum Settlement for Strain	Strain Criteria, ε_{max} = 0.1%
feet:	18	0.1%

remaining settlement

16.7 feet

if less than greatest allowable settlement, ok

Cover Slope Settlement Calculation
Calculation performed for the center of the landfill

Cap slope	Raise in surface at landfill center (ft)	Subsurface Consolidation Settlement (ft)	Cover Consolidation Settlement (ft)	Raise in surface to maintain 3% slope (ft)	Maximum settlement to maintain 3% slope (ft)	Allowable degradable thickness (ft)	Length of slope (ft) : 500
3%	15	1.2	0.1	15	-1.3	-8.7	15%
4%	20	1.2	0.1	15	3.7	24.7	percent
5%	25	1.2	0.1	15	8.7	35.0	degradable settlement
6%	30	1.2	0.1	15	13.7	35.0	
7%	35	1.2	0.1	15	18.7	35.0	
8%	40	1.2	0.1	15	23.7	35.0	
9%	45	1.2	0.1	15	28.7	35.0	
10%	50	1.2	0.1	15	33.7	35.0	

	Maximum Settlement for Strain	Strain Criteria, ε_{max} = 0.1%
feet:	23	0.1%

Remaining settlement

21.7 feet

if less than greatest allowable settlement, ok

Cover Slope Settlement Calculation
Calculation performed for the center of the landfill

Cap slope	Raise in surface at landfill center (ft)	Subsurface Consolidation Settlement (ft)	Cover Consolidation Settlement (ft)	Raise in surface to maintain 3% slope (ft)	Maximum settlement to maintain 3% slope (ft)	Allowable degradable thickness (ft)	Length of slope (ft) : 300
0.03	9	1.2	0.1	9	-1.3	-8.7	15%
0.04	12	1.2	0.1	9	1.7	11.3	percent degradable settlement
0.05	15	1.2	0.1	9	4.7	31.3	
0.06	18	1.2	0.1	9	7.7	35.0	
0.07	21	1.2	0.1	9	10.7	35.0	
0.08	24	1.2	0.1	9	13.7	35.0	
0.09	27	1.2	0.1	9	16.7	35.0	
0.1	30	1.2	0.1	9	19.7	35.0	

	Maximum Settlement for Strain	Strain Criteria, ε_{max} = 0.1%
feet:	14	0.1%

remaining settlement
12.7 feet
if less than greatest allowable settlement, ok